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Regional scale mapping of ecosystem services supply, demand, flow and mismatches in Southern Myanmar

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ABSTRACT

Mapping ecosystem service (ES) supply, demand, and flow – and identifying supply/demand mismatches – has become a focus of ES research and has benefitted from recent advances in modelling techniques and their combination with Geographic Information Systems. But few studies have been done in data-scarce tropical forest frontiers and these were limited in terms of area, land uses, and number and types of ES. Aiming to evolve contemporary approaches, we used Bayesian networks to model and map nine ES across Myanmar's Tanintharyi Region for local stakeholders. Results show that while there is a high supply of multiple ES at regional level, demand for ES in urban and rapidly developing agricultural areas is not fully covered. Further, we identified a clear connection between land tenure and ES outcomes for rural communities. Agricultural concessions and protected areas with restricted access for the local population were related to lower ES flows and more supply/demand mismatches than community forests or untenured land. For future research on local ES outcomes in tropical forest frontiers, we recommend combined mismatch and flow analyses under consideration of tenurial rights.

1. Introduction

Human–nature interrelations are becoming ever more apparent in the joint search for solutions to global goals of biodiversity conservation, climate change mitigation, economic development, and human well-being (UN, 2015). In forest frontier landscapes, trade-offs almost always occur in efforts to achieve both ecological and social goals, especially if policies fail to take a holistic approach. Within such landscapes, the concept of ecosystem services (ES) (Costanza et al., 2017) is highly useful for assessing the multiple benefits people obtain from different landscapes. First popularized in 1997 (Costanza et al., 1997), the concept was applied at a larger scale in the Millennium Ecosystem Assessment (MEA, 2005) and has since seen various adaptations. It has also evolved into further concepts, such as that of nature's contribution to people by the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (Díaz et al., 2018). The ES concept nevertheless remains the most suitable way to assess local relations between humans and nature in an integrative way (Braat, 2018; Pandeya et al., 2016). Meanwhile, research on ES has made much progress on different valuation methods (Gómez-Baggethun et al., 2016) and on modelling and mapping (Willemen et al., 2015). Mapping is an important tool for policymakers to better understand the links between ecosystems, society, and human well-being (Burkhard and Maes, 2017). In the last decade, spatial assessments of ES have thus become increasingly relevant and have evolved by including demand (Schröter et al., 2012; Wolff et al., 2015) as well as flows (Bagstad et al., 2013; Baró et al., 2016; Schirpke et al., 2019).

While simple mapping methods showing ES provision scores by land cover type are particularly useful in data-scarce regions, they do not usually reflect the dynamics of supply and demand. Using expert

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valuation, Burkhard et al. (2012) included demand for a variety of ES based on land cover types. Other studies added the notion of ES flows to show whether potential services can be accessed by people. One of the most comprehensive studies so far mapped supply and flow of, and demand for, eight ES in the European Alps, and assessed the respective ES bundles (Schirpke et al., 2019). Mapping ES supply, demand, and flow can inform policymakers of a potential mismatch in a certain area, through unsatisfied demand or overuse (Geijzendorffer et al., 2015). Several studies have mapped such mismatches between supply and demand in the northern hemisphere (Baró et al., 2016; Burkhard et al., 2012; Chen et al., 2020). But remaining challenges are the lack of empirical data and participatory approaches to include stakeholder perceptions (Baró et al., 2016).

In tropical regions, recent notable mapping studies presented trade-offs between three services in Ecuador (Forio et al., 2020), (mis)matches and trade-offs in Brazil (Pinillos et al., 2020), and spatial equity in accessing services in ES hotspots in forested landscapes of Suriname (Ramirez-Gomez et al., 2020). However, due to the inherent complexity of socio-ecological systems and data scarcity in many tropical regions, ES assessments in the tropics remain limited in terms of area, land uses, and number and types of services investigated. Furthermore, mapping studies have considered mostly ES that are important from a public perspective such as carbon sequestration, water regulation, food production, or recreation and tourism (Malinga et al., 2015). There is an inherent need to better include the perspective of local stakeholders such as smallholder farmers and forest-dependent people into the modelling and mapping process (Willemen et al., 2015), particularly in contested frontier regions.

In tropical forest frontier landscapes such as Myanmar's Tanintharyi Region, where overlapping land claims cause conflicts and hinder sustainable development planning (Schneider et al., 2020), spatial ES assessments can provide opportunities to identify local stakeholder needs and plan landscape development accordingly. In Tanintharyi, the remaining large, intact, and mostly undisturbed natural forest landscapes are under increasing pressure from infrastructure development, agricultural expansion, mining, and overuse (de Alban et al., 2019; Lim et al., 2017). The situation is further aggravated by conflicting interests between local communities, the private sector, and government institutions. A global biodiversity hotspot (Myers et al., 2000), Tanintharyi is increasingly characterized by large-scale oil palm concessions (Woods, 2016), private rubber plantations (Vagneron et al., 2017), and mining (LaJeunesse-Connette et al., 2016); it is also the location of a Special Economic Zone, with plans for development (Walsh, 2015). Priority issues at the global level include biodiversity and climate change mitigation, but local stakeholders may require different ES from land systems. In northern Tanintharyi, where rural communities use the land for shifting cultivation, mixed betelnut and cashew plantations, rubber plantations, and to gather non-wood forest products, ES associated with these land uses were found to be essential for the well-being of the inhabitants (Feurer et al., 2019). Unfortunately, local communities have little say when it comes to the use of land and are thus limited in their access to ES, especially in zones allocated to government entities or concessionaires (Feurer et al., 2019). Understanding spatial ES outcomes for local stakeholders by analysing supply, demand, and flow – and to what extent they are matched or mismatched – is a crucial step towards formulating adequate policies for more sustainable landscapes and human well-being.

Until now, few studies have attempted to map both ES supply and demand in tropical forest frontiers, and none have combined the analysis of supply/demand (mis)matches with considerations of access to give an adequate representation of actual ES outcomes for local stakeholders, which is a particularly sensitive issue in forest frontiers (Ramirez-Gomez et al., 2020).

Recognizing this gap, the objective of this study is to identify spatial supply/demand (mis)matches of nine ES (subsistence foods, commercial products, fuelwood, medicinal plants, biodiversity, climate regulation, water regulation, environmental education, cultural identity) in a tropical frontier landscape. It further aims to map ES flows based not only on distance but also on land tenure and zoning. By applying previously developed empirical ES models on the basis of Bayesian networks [Feurer et al., 2021] and incorporating ecological and socio-economic data sets from Tanintharyi Region using the gBay tool (Stritih et al., 2020), this study aims to spatially assess ES outcomes from a perspective of local stakeholders across the region.

The study was guided by the following research questions:

a) What is the regional extent and spatial distribution of the supply, demand, and flow of nine ES for local stakeholders?
b) What are the supply and demand balances for nine ES across Tanintharyi Region?
c) How frequent and intense are ES mismatches illustrated at different spatial scales?

2. Material and methods

2.1. Study area

Tanintharyi Region in Myanmar's South is situated between Mon State in the North, Thailand in the East and South, and the Andaman Sea in the West. It encompasses 4.3 million ha of land including a large number of islands. Land cover is mostly forest along the hilly areas near the Thai border, with degraded forest patches and both large-scale (oil palm, rubber) and small-scale (rubber, mixed) plantations near the roads (Fig. 1). Oil palm plantations are found mainly in the southern part near Kawthoung, while rubber plantations are concentrated around Dawei in the northern part. Mangrove forests are most prevalent near Myeik and in the archipelago. Paddy rice production is common in the flat areas near villages and roads. Most villages are located near the main roads, with most of Tanintharyi's 1.4 million-strong population (DOP, 2014) living in these areas.

Tanintharyi Region is one of the focal areas of the OneMap Myanmar initiative, which aims to improve country-wide accuracy and availability of data on land use, land cover, and land tenure by combining official sources with participatory mapping and public contributions. Thus, Tanintharyi has a relatively good availability of land use data compared to other regions of Myanmar. There are currently two protected areas (Tanintharyi Nature Reserve and Lampi National Park); a further two were proposed in 2002 but are contested due to the top-down approach of the proposals (Lenya National Park and Tanintharyi National Park). In addition, there are a total of 69 formal community forests (OMM, 2018b) as well as several informal community protected areas. In another development, concession lands have been granted to various companies since the early nineties, with 7.5% and 0.1% of Tanintharyi's land area under oil palm and mining concessions, respectively (Feurer et al., 2021). The remaining land is under the relevant government departments, where local land users can apply for formal user rights. However, much of the cultivated land, including shifting cultivation areas, is managed through customary rights.

2.2. Theoretical framework

This research builds on current understandings of the ES concept (Costanza et al., 2017) and recent advances in ES mapping (Burkhard and Maes, 2017; Willemen et al., 2015). The underlying idea is that final ES outcomes are influenced by the supply and flow of, and demand for, such services (Feurer et al., 2021; Geijzendorffer et al., 2015; Schirpke et al., 2019). While *ES supply* encompasses the goods and services provided by nature, *ES demand* refers to the use and perceived value of these goods and services. Finally, *ES flow* refers to people's access to the goods and services they require. We consider ES supply to be the result of biophysical factors such as vegetation, climate, soil type or slope, and land management aspects including land use, agricultural practices, or

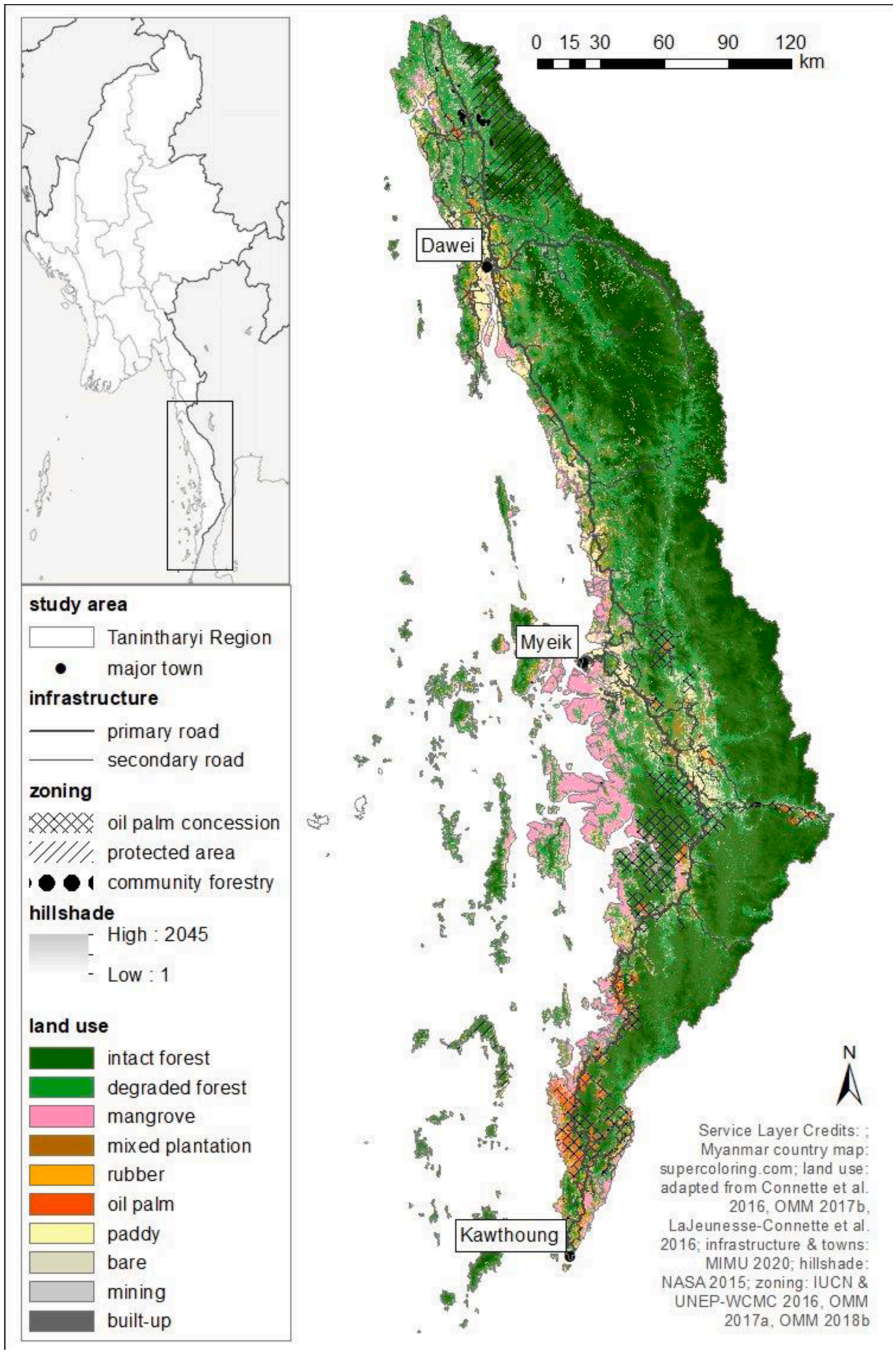


Fig. 1. Map of the study area (land use adapted from Connette et al. (2016)).

chemical inputs. ES demand, on the other hand, is the result of the perceived benefits, including non-material and intrinsic values, and actual use by the local people based on population density and the local availability of substitutes, e.g. modern medicine instead of traditional herbal remedies. We consider ES flow to represent people's access to service providing areas, consisting of physical accessibility based on distance, institutional accessibility based on zoning (protected area, community forest, concession), and tenurial rights.

Nine ES were selected based on the Common International Classification of Ecosystem Services classes (Haines-Young and Potschin, 2018), with adaptations to the local context. The main selection criteria were: coverage of at least one provisioning, regulating, and cultural service, a link to dominant land uses in the study area, relevance for local stakeholders (based on a ranking exercise in three villages), secondary data availability, suitability for modelling, and relevance for policymakers (based on a literature review). The selected ES are: subsistence foods, commercial products, fuelwood, medicinal plants, biodiversity, climate regulation, water regulation, environmental education, and cultural identity.

2.3. ES models

Bayesian networks (BN), which have gained attention in ES modelling and mapping (Burkhard and Maes, 2017), are probabilistic models resting on causal dependencies (Kjærulff and Madsen, 2008). They include one or several root nodes (input variables), structuring intermediary nodes, and end or target nodes (output variables). BN are particularly useful in data-scarce regions; advantages include their ability to integrate different types of data and knowledge sources as well as their handling of uncertainties by operating with probabilities. These features contribute to the recommendations by Willemen et al. (2015) for mapping ES: robustness, transparency, and stakeholder relevance. In spatially explicit applications of BN, uncertainties can be illustrated for example in the form of an evenness index of probable values (Stritih et al., 2020). We adopted previously developed BN (Feurer et al., 2021) and updated them with secondary data on Tanintharyi Region (see Section 2.4.1) using Netica commercial software (version 6.05). The models had been developed in a comprehensive iterative process of several steps and three main phases: defining model structures, construing conditional probabilities, and calibrating and validating final models. The process was grounded on a comprehensive literature review and three months of field research between 2017 and 2020 by the first author. The field research included transect walks; field observations and focus group discussions in eight villages in three townships; a household survey (n = 40); and 15 in-depth interviews with local experts from non-governmental organizations, civil society, and research institutions active in the study area. More details are found in Feurer et al. (2021). The final BN thus incorporate various data types including available geodata, a population census, and qualitative data. Each of the nine BN had the end nodes ‘supply’ and ‘demand’ with five values on a scale of 1 (very low) to 5 (very high), as well as ‘flow’ with three respective values from 1 (low) to 3 (high). The relationships between variables as well as end values are determined by a mix of literature and social valuation and presented as probabilities (ibid.). The input variables, for which categorical spatial data was added for this study, are listed in Table 1. The complete BN are displayed in the Annex.

Certain limitations of the models relating to representativeness across the region must be acknowledged. Reasons for these limitations include the vastness of the area investigated, the limited availability of data, the low accessibility of some areas of the region, and the high diversity in both land use and culture. While the models take the perspective of local stakeholders, notably rural communities, the perception of certain minority groups are not fully accounted for. These include, among others, internally displaced people living in the Tanintharyi hills, the Moken living on the sea, and migrant workers staying in concession areas.

Table 1
Main model variables considered as determinants for supply, demand, and flow in relation to nine ecosystem services derived from the Common International Classification of Ecosystem Services (CICES).

Ecosystem service	Supply variables	Demand variables	Flow variables
Subsistence foods	Land use	Land use (food type) Population density Residential area	Distance to village
Commercial products	Land use Slope Soil type Wet months	Land use (type of product) Population density Residential area Township (employment rate)	Township (means of transport) zoning
Fuelwood	Land Use	Population density Residential area Township (fuel type)	Distance to village Slope Zoning
Medicinal plants	Key biodiversity area Land use Zoning (land management)	Distance to forest Population density Residential area	Distance to village
Biodiversity	Distance to forest Key biodiversity area Land use Zoning (land management)	Land use Population density Residential area Township (employment sector)	Distance to agriculture Distance to village
Climate regulation	Land Use	Distance to bare land Population density Residential area Township (employment sector)	Distance To Village
Water regulation	Annual precipitation Land use Residential area (pollution) Slope Soil type Wet months	Land use (type of product) Population density Township (water source)	Township (water source)Zoning (watershed protection)
Environmental education	Land use Zoning (vocational training)	Population density Residential area Township (employment sector)	Residential areaTownship (internet)
Cultural identity	Land use Land use changeTownship (mobiles phones)	Land use (cultural products) Population density Residential area	Distance to village Zoning

2.4. Mapping process

2.4.1. Data sources and processing

The ES maps produced are based on currently available secondary data for the study region as well as primary data collected for this research and included in the BN. For the selection of the most accurate and recent data for this study, the following criteria were used: Availability (published or made available by the OneMap Myanmar project), scope (covering the entire Tanintharyi Region), date (most recent), and accuracy (according to the authors’ knowledge on the situation on the ground).

All data sets were pre-processed in ArcGIS (V 10.6.1) to fit the same extent, include only relevant classes, and show consistency with the categories used in the ES models. All vector data were first converted to raster data. At the end, all raster files were stored in .tif format and clipped to the extent of the land use raster with the same resolution as the original raster (31 m × 31 m). Table 2 lists all data sets underlying the ES models, the original sources, and the relevant pre-processing that was done.

2.4.2. Generating spatial model outputs

We used an online tool, gBay, (Stritih et al., 2020) to link the BN with the respective spatial data. BN models were uploaded to the tool in .dne format and spatial data were uploaded in .tif format. The gBay tool then connected the spatial data (raster cells) with the BN provided. In the spatial data sets (e.g. on land use or soil type), each pixel has a specific value (e.g. oil palm or nitisol), which provide the evidence for the BN’s root nodes. We then calculated the rest of the nodes with the underlying conditional probabilities of the BN and produced as output the posterior probability of each possible value for the determined target nodes

Table 2
List of spatial data sets, sources, and pre-processing steps carried out in ArcGIS (V 10.6.1).

Data set	Subset	Source(s)	Pre-processing
Land use	All land use classes	Connette et al. (2016)	• Reclassify 16 land cover classes into 9 land use classes → *landuse9*
	Oil palm (planted)	OMM (2017b)	• Reclassify to oil palm and built-up • Multiply with *landuse9* and reclassify (rubber where no oil palm planted in second data set) → *landuse9_op*
	Mining areas	LaJeunesse-Connette et al. (2016)	• Reclassify (yes, no) • Multiply with *landuse9_op* and reclassify → *landuse10*
Zoning	Protected areas	IUCN and UNEP-WCMC (2016)	• Delete features (proposed protected areas) • Reclassify (yes, no)
	Community forests	OMM (2018b)	• Reclassify (yes, no)
	Mining concessions	OMM (2018a)	• Delete feature (large overlapping concession area) • Reclassify (yes, no)
	Oil palm concessions	OMM (2017a)	• Reclassify (yes, no)
	SEZ (Special Economic Zone)	MIMU (2020)	• Combine all and reclassify
Key biodiversity area		BirdLife International (2010)	• Delete features (marine protected areas) • Reclassify (yes, no)
Slope		NASA (2015)	• Classify (flat if < 30%, slope if ≥ 30%)
Soil type		FAO (2007)	• Dissolve according to main soil types (acrisols, gleysols, fluvisols, nitrosols)
Precipitation		WorldClim (2012)	• Combine rasters (PPET 1 – 12) • Add field and calculate annual precipitation • Reclassify into 5 classes according to model
Wet months		WorldClim (2012)	• Calculate number of wet months • Add field and classify (1–3, 4–6, > 6)
Residential area		Worldpop (2016)	• Classify (rural if < 4 pph, urban if ≥ 4 pph)
Township		MIMU (2020)	
Population density	Village tracts	MIMU (2020)	• Add field in attribute table (pp/ha) • Classify (high if, medium if, low if)
Land use change		Schmid et al. (2021)	• Reclassify (yes, no)
Distance to agriculture		based on *landuse10* (see above)	• Agriculture = mixed plantation, oil palm, paddy, rubber • Calculate Euclidean distance for maximum of 10 km
Distance to forest		based on *landuse10* (see above)	• Forest = intact forest • Calculate Euclidean distance
Distance to bare land		based on *landuse10* (see above)	• Bare land = bare, mining, built-up, paddy • Calculate Euclidean distance for maximum of 3 km
Distance to village	Villages	MIMU (2020)	• Calculate Euclidean distance

(ibid.). In our case, the target nodes were 'supply', 'demand', and 'flow' for all nine ES models. The supply and demand nodes had five values on a scale of 1 to 5, with 1 representing a very low outcome and 5 representing a very high outcome. Flow nodes had three respective values on a scale of 1 to 3. After updating the BN with spatial data (i.e. hard evidence), gBay produced outputs in the form of a multi-band raster (in .tif format) for each determined target node. The multi-band raster consisted of one band per value showing their respective probability and an additional band with the most likely state number of a target node. Further, gBay provided an additional multi-band raster including some basic statistics (Shannon's evenness index, mean, median, standard deviation). The Shannon's evenness index reflects a measure of uncertainty and ranges between 1 (uniform distribution and maximum uncertainty) and 0 (complete certainty) (ibid.).

2.5. Data analysis (outputs)

All outputs including nine ES supply, demand, and flow maps were closely examined for plausibility in ArcGIS by comparing them with the land use map and by zooming in on different areas. The analysis was supported by field observations by the first author of this paper from a total of three months spent in Tanintharyi Region between 2017 and 2020. To examine the supply, demand, and flow outputs, we operated with the most likely values (1 to 5 and 1 to 3, respectively) and additionally displayed evenness indices representing map uncertainties. Spatial statistics were calculated in ArcGIS. In addition to supply, demand, and flows, spatial supply/demand balances were calculated by subtracting the most likely demand value (between 1 and 5) from the most likely supply value (between 1 and 5). This led to ES balances in the range from −4 (demand > supply) to 4 (supply > demand). The resulting ES balance maps show positive values where potential supply outweighs local demand and negative values where demand exceeds supply. All negative balances were termed mismatches. Two sets of spatial analyses were done (frequency and intensity of mismatches) combining the nine ES balances. The frequency analysis consisted of summing up the number of ES presenting mismatches (balance < 0) per pixel, resulting in a theoretical range from 0–9. For the intensity analysis, we first inverted all negative balance values (balance < 0) into positive mismatch values (-4 to 4, −3 to 3, etc) to simplify further analyses. We then added the mismatch values of all nine ES, resulting in a theoretical range from 0–36. In a final step, these mismatches were contextualized in more detail for two case study sites where extensive combined field experience by several of the authors provided reliable insight. The two sites were selected based on the following criteria: representativeness of land uses, occurrence of mismatches, and contextual information from field research. Study site A is located in Yebyu township and represents a typical frontier landscape with high development and various zoning arrangements such as a protected area, community forests, and an oil palm concession. Study site B encompasses the coastal town of Myeik and some surrounding areas including paddy fields and mangroves. Both study sites were analysed in terms of mismatch frequency and intensity. In order to contextualize them more accurately, the prevalence of mismatches for each ES was additionally calculated as the percentage of pixels (% per area) presenting a mismatch for the respective ES in each study site.

3. Results

3.1. Ecosystem services distribution in Tanintharyi Region

3.1.1. ES supply

Results show that six of the ES investigated are in high supply in

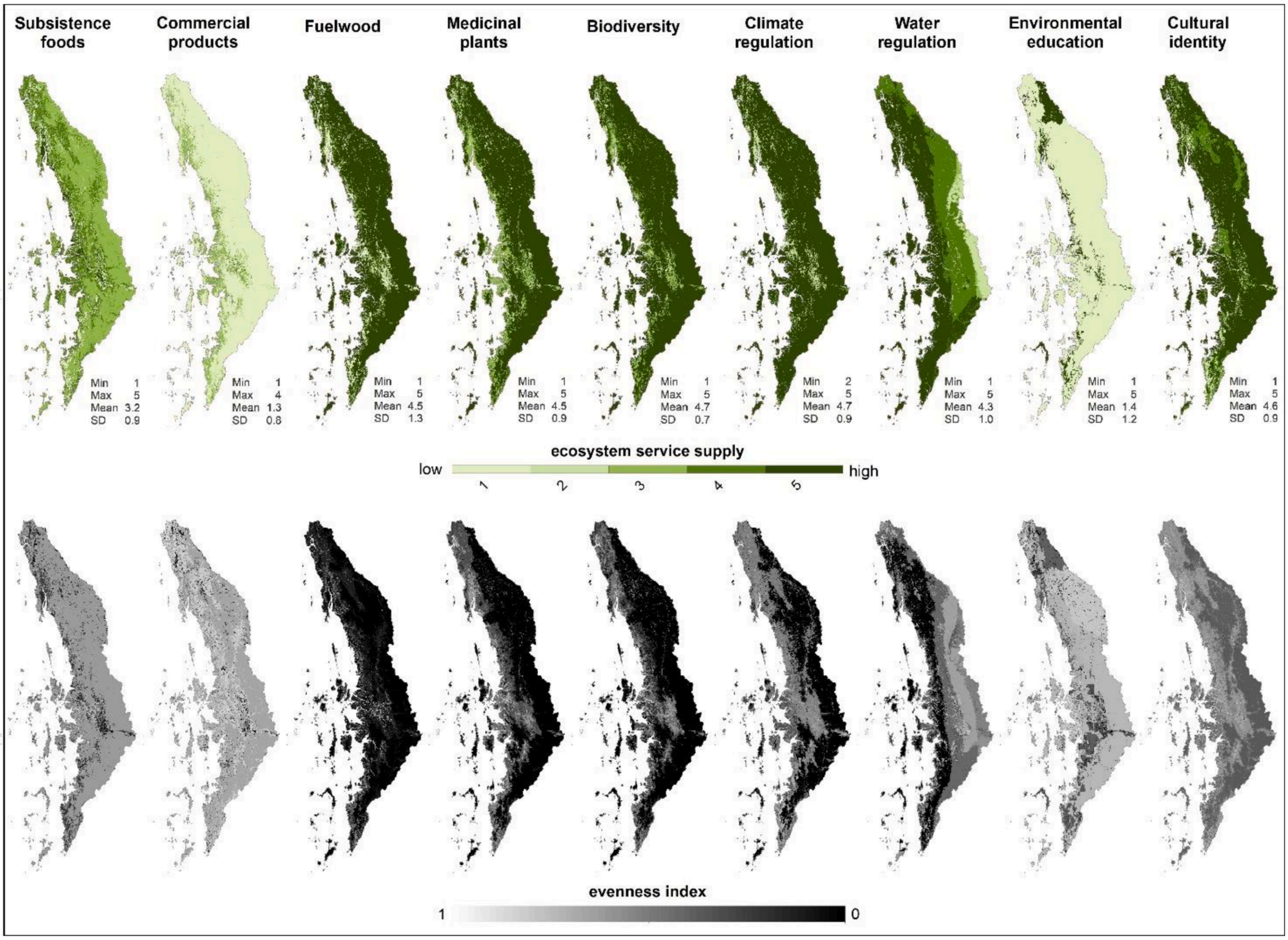


Fig. 2. Ecosystem service supply in Tanintharyi Region. *Above*: most likely ES supply values according to the models; *below*: corresponding evenness index representing uncertainty of those values (1 = maximum uncertainty, 0 = no uncertainty).

Tanintharyi, with values of ≥ 4 in most parts of the region (Fig. 2). Forest-related ES including fuelwood, medicinal plants, biodiversity, climate regulation, and cultural identity are provided throughout Tanintharyi, with mean values of 4.5 and above and only a few low-supply areas near roads and towns. Our findings reflect the strong link between land use and ES provision, even though the models included other variables. Interestingly, although protected areas are often established with the goal of safeguarding regulating services, our findings indicate that ES supply for local stakeholders is just as high outside of those where forests remain intact. While the importance of forests and mangroves for providing regulating ES is evident, regulating ES are also to some extent provided in areas dominated by agricultural plantations. Subsistence foods are provided largely in agricultural areas but also in forested uplands, where shifting cultivation and gathering of non-wood forest products still play an important role. The lowest supply by far was found for commercial products (mean = 1.3), and they are confined to agricultural and coastal lands. In coastal areas, mangroves provide commercial products mainly in the form of fisheries. Although forests theoretically also provide timber and valuable non-wood forest products, rural communities make little commercial use of those due to legal restrictions and limited marketing opportunities. Another noteworthy result is shown for environmental education. Even though the provision of educational services is limited overall (mean = 1.4), opportunities for environmental or agricultural training exist both in sites with agricultural development and in protected areas. The low supply of water regulation in the highly forested area to the east may be surprising. However, this can be explained by the comparatively low annual rainfall in the area covered in the model and does not appear to reflect land use or soil properties.

Across all ES, we found a relatively low mean evenness index of 0.37, indicating little variation in the probability distribution, hence the displayed values are relatively distinct from the other possible values. ES with high supply values such as fuelwood, medicinal plants, or biodiversity have few variations in their probability distributions and express more certainty. Similarly, for all ES, areas with higher supply values correspond to lower uncertainties. Accordingly, lower supply values are associated with higher uncertainties. The low supply values of commercial products and environmental education displayed are thus subject to high uncertainties with mean evenness indexes of 0.68 and 0.64, respectively. Due to these high variations in the distribution of probable values, it can thus be assumed that the maps of most likely values for commercial products and environmental education supply depict a rather conservative picture.

3.1.2. ES demand

Demand varies more than supply across the nine ES, particularly in remote areas (Fig. 3). Higher population densities in urban and peri-urban areas prompt a higher demand for ecosystem goods such as subsistence foods, commercial products, fuelwood, and medicinal plants. Commercial products have a higher importance for the more market-oriented communities living near roads and towns. On the contrary, biodiversity is valued more by rural communities, which depend largely on agriculture and natural forests for their livelihoods. The overall high value of biodiversity (mean = 4.8) hinges on several variables included

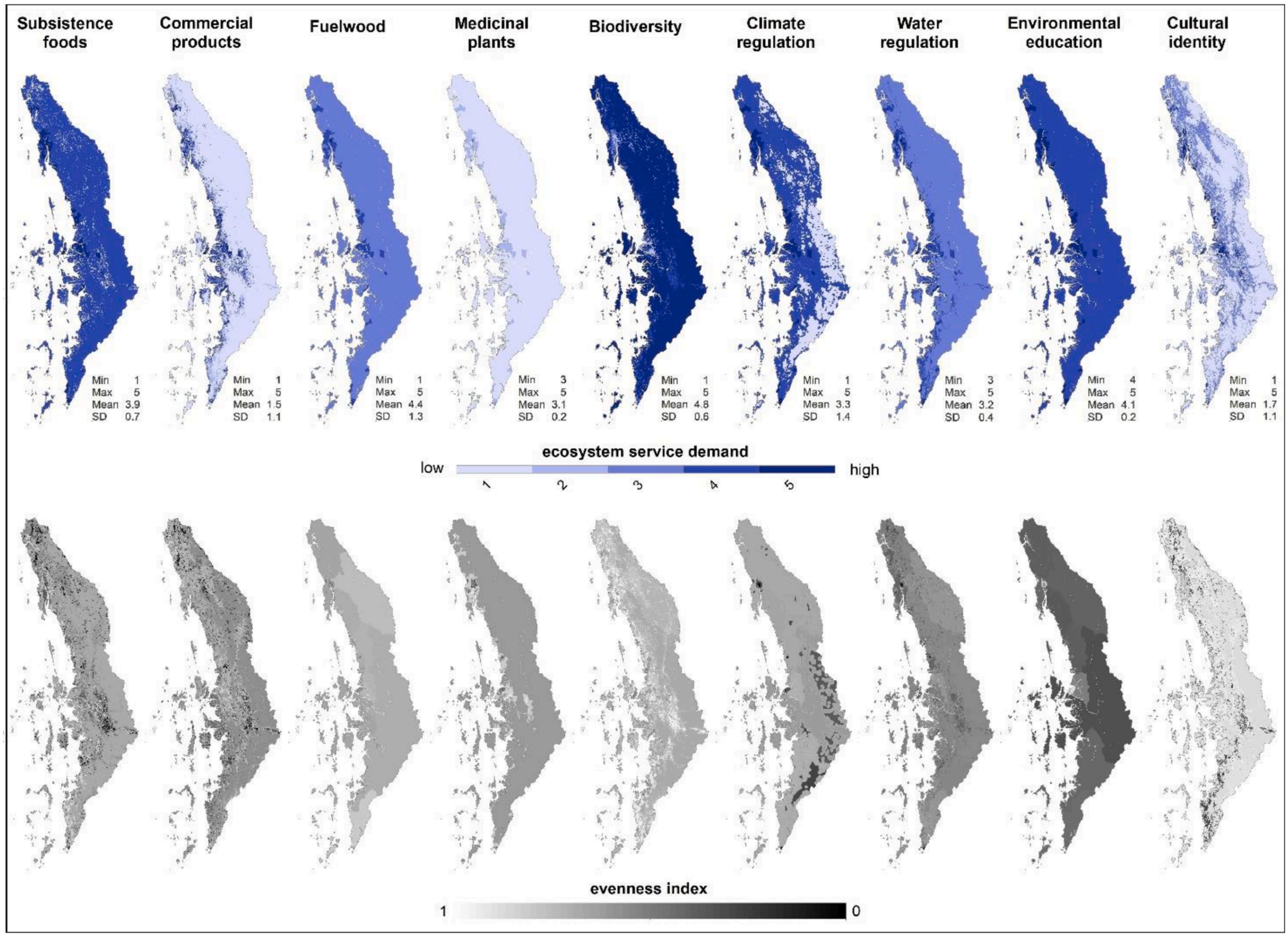


Fig. 3. Ecosystem service demand in Tanintharyi Region. *Above*: most likely ES demand values according to the models; *below*: corresponding evenness index representing uncertainty of those values (1 = maximum uncertainty, 0 = no uncertainty).

in the model: direct use of non-wood forest products, indirect benefits through pollination, and intrinsic value. After biodiversity, local communities also have a strong demand for environmental education (4.1), subsistence foods (3.9), water regulation (3.2), and fuelwood (3.1). The results for subsistence foods and fuelwood shows that although population density is low in remote areas, demand for ES remains high, as these communities have limited access to markets and are dependent on subsistence products with few alternatives. What may be surprising is the low result for both medicinal plants (1.1) and cultural identity (1.7). This reflects the increasingly available and attractive alternatives, including modern medicine but also cultural attractions that are unrelated to nature. On the other hand, interpretation of the results in very remote areas should take into account that internally displaced people and other remote communities were not involved in developing the model. This is underscored by the high uncertainty in demand values for cultural identity throughout the region, but particularly in remote areas.

Compared with supply, we also found a higher overall evenness index across ES (mean = 0.63) and thus more uncertainties related to the displayed demand values. The displayed low demand for cultural identity, particularly in remote forested areas, is subject to high uncertainties. In contrast, a combination of high values and low uncertainty was found for environmental education, confirming the widespread demand also experienced during our field visits.

3.1.3. ES flow

Our results illustrate two clear patterns of ES flow. First, flow is higher near roads and settlements (Fig. 4). Naturally, these areas are more accessible due to physical proximity, largely flat terrain, and existing infrastructure. Second, rural communities can readily make use of some ES including water, medicinal plants, and fuelwood, whereas access to other ES is considerably more restricted. Our results further illustrate the impact of zoning (protected areas, community forests, concessions) on local ES flows. The fact that local communities are often prohibited from entering protected areas or concession lands limits their access to ES provided by these lands. The access limitations of concession lands located in the South are well visible for provisioning services including commercial products and fuelwood and even cultural identity. We found that protected areas, while not restricting cultural identity, have a similar effect on provisioning services. Limited access to conserved forest lands can thus reduce local ES outcomes from these areas, at least temporarily.

The evenness index differs strongly across the nine ES. Displayed flow values of subsistence foods and climate regulation are relatively distinct with a mean evenness index below 0.5. But flow values of medicinal plants, environmental education, and commercial products show more variation in their probability distributions. The displayed values are highly uncertain with respective mean indices of 0.9 and above. In contrast to ES supply, a low evenness index (high certainty) does not correspond to high values for ES flows.

3.2. Supply and demand balances

Comparing the nine ES, results show that only biodiversity and commercial products, at least in rural areas, are balanced, where supply

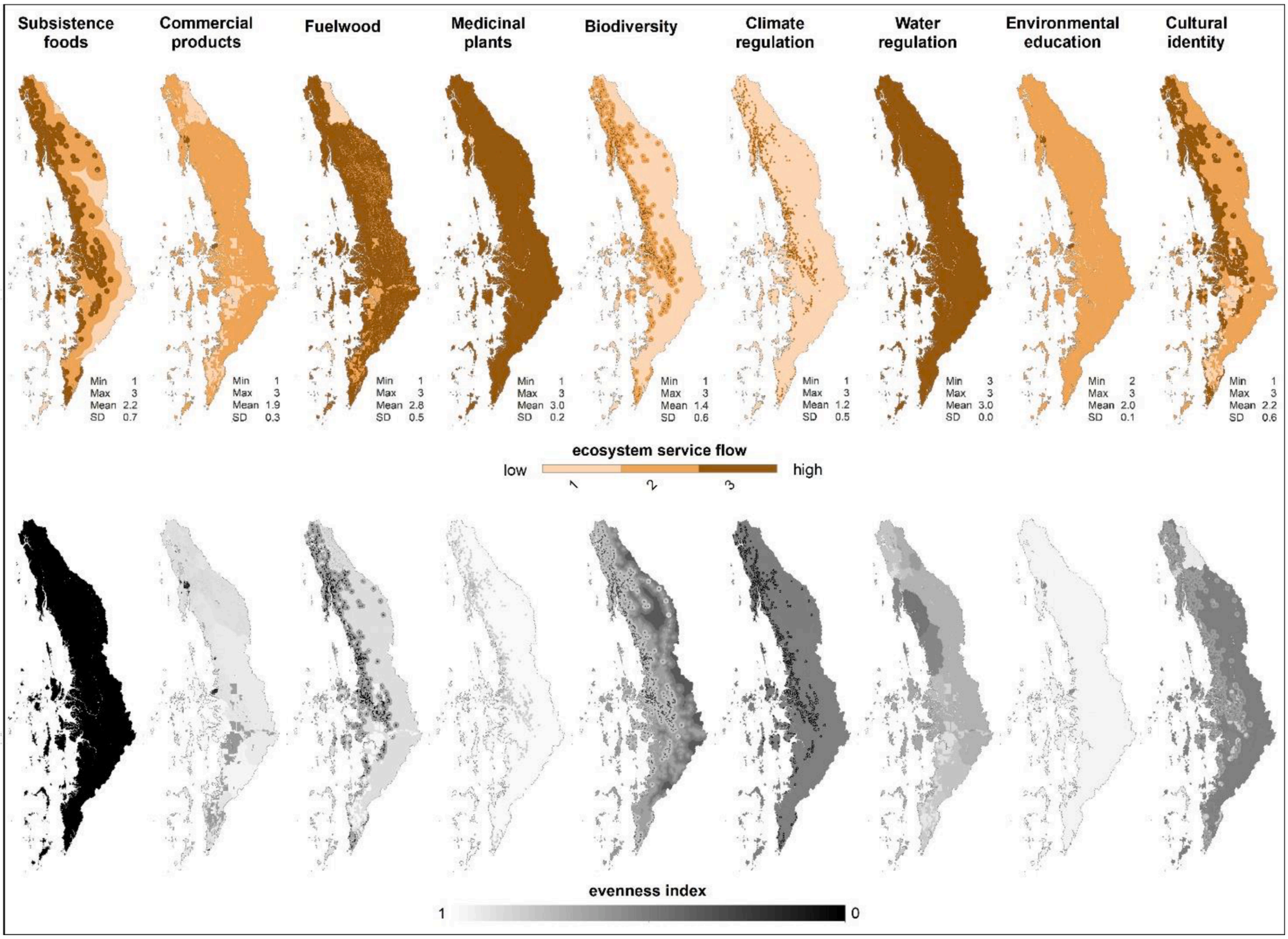


Fig. 4. Ecosystem service flow in Tanintharyi Region. *Above*: most likely ES flow values according to the models; *below*: corresponding evenness index representing uncertainty of those values (1 = maximum uncertainty, 0 = no uncertainty).

approximately covers local demand (Fig. 5). Medicinal plants and cultural identity are oversupplied or underutilized. For all other ES we identified larger mismatch areas (supply < demand). Critical mismatches were found for environmental education, which the communities interviewed often described as a major limitation, as well as subsistence foods in large areas of Tanintharyi. Although these ES are in high demand by local stakeholders, supply is limited throughout the region. Overall, map uncertainties (high evenness index) were found to be more common in areas that display a negative ES balance (a mismatch). On the other hand, positive ES supply and demand balances between 0 and 4 seem to be linked to higher map certainties (e.g. subsistence foods, fuelwood, medicinal plants, climate regulation, environmental education).

Geographically, the most adversely affected areas are found along roads, in urban and peri-urban areas, and in sites facing agricultural expansion. In contrast, large landscapes along the forested eastern border provide a local surplus in fuelwood, medicinal plants, climate regulation, and cultural identity.

While large forest complexes in rural upland areas contribute to climate regulation, this is not the case in large settlements, rice producing areas, and other bare lands, where the microclimate is often problematic during the summer. Towns and coastal sites with many fish factories experience reduced air quality. In addition, coastal regions are more directly affected by climate change through sea level rise and increased frequency and intensity of cyclones, and therefore people living there may be more sensitized to climate issues. Thus, demand for more trees in the landscape is highest in these areas, leading to strongly negative ES balances (-3). Water regulation, on the other hand, seems to be balanced regionally. The only mismatch (-1) is found where annual rainfall is comparatively low. But we also detected small patches with stronger mismatches (-4) in some of the more developed zones. With the high seasonality of rainfall in Tanintharyi, it is possible that certain coastal areas face water scarcity particularly during the summer. According to our results, environmental education is the ES that is by far the most affected by negative supply/demand balances. Demand for environmental education, which is heavily linked to agricultural and environmental capacity building, is extremely high in both rural and urban areas and is driven by people's dependence on agriculture and natural resources for their livelihoods, a genuine interest and cultural connection to the environment, and a generally strong desire to learn new things. But with no functioning extension services there are very few opportunities for smallholders to attend formal training. Notable exceptions with positive supply/demand balances are found in the two protected areas (+1). This is linked to the fact that establishing a protected area often involves capacity building activities on environmental management and conservation. This is sometimes coupled with livelihood projects and agricultural training. On the other hand, there are few communities living within the protected areas, which leads to an overproportioned supply. For subsistence foods, there is a distinct divide between balanced areas and those where local demand cannot be met with local supply. Balanced areas are coastal and other low-lying areas with adequate road networks where smallholder agriculture and paddy fields are common. Proximity to roads and access to foods from markets further reduces the need for these communities to produce their own

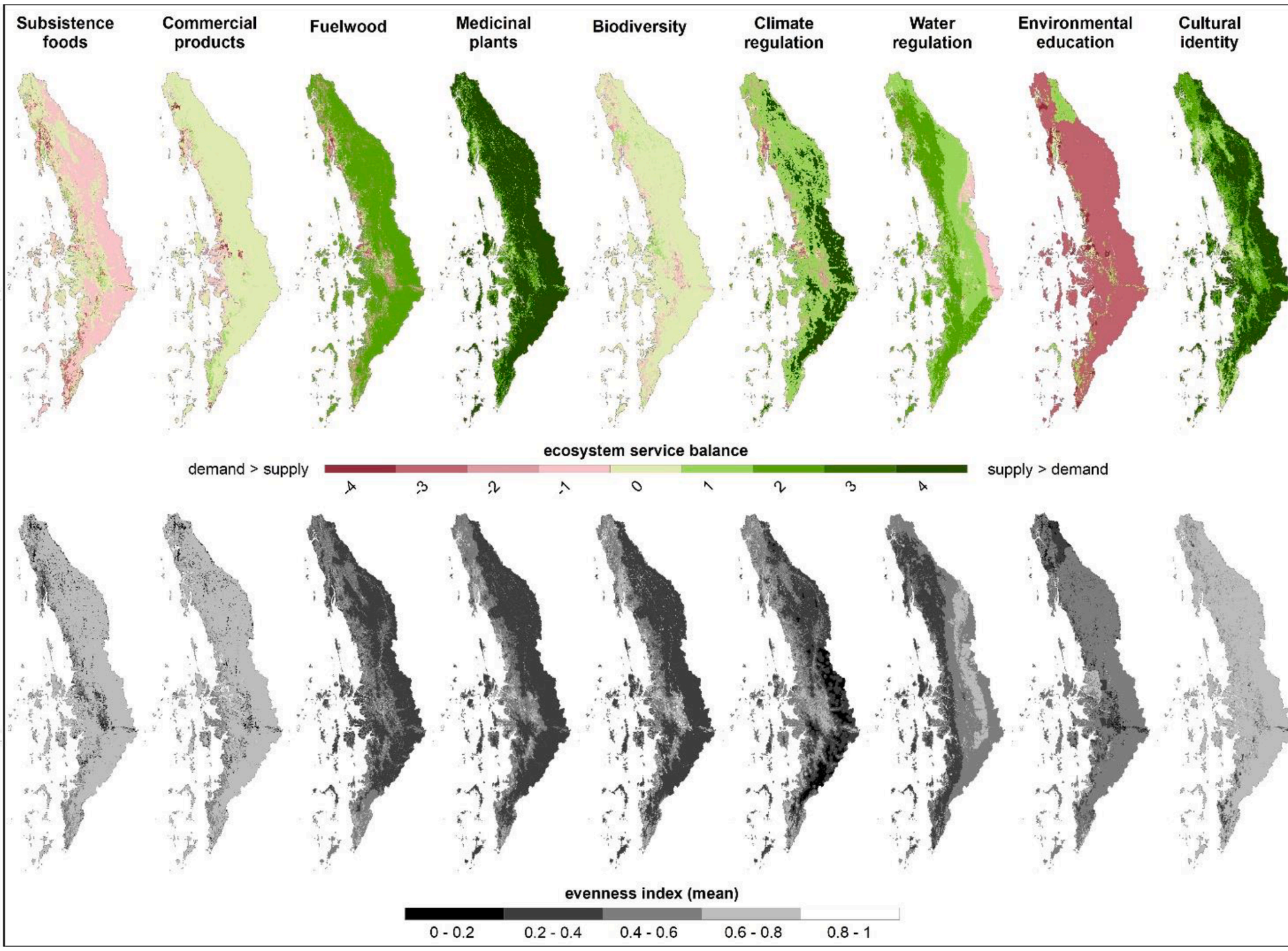


Fig. 5. Ecosystem service balances (supply–demand) in Tanintharyi Region. *Above*: ES balances calculated as most likely supply values minus most likely demand values, with red areas illustrating mismatches; *below*: classified evenness index calculated as the mean of supply and demand indices, representing uncertainty of the mapped ES balance values (0 = no uncertainty, 1 = maximum uncertainty).

food. This is different in the hilly areas where forest landscapes dominate. The few communities living there rely on shifting cultivation and on the wild foods they can gather from forest and fallows. This is represented in only a slightly negative balance (−1). More severe mismatches are admittedly found in oil palm concessions in Tanintharyi's southern part (−3) and in some urban and peri-urban areas, especially around Dawei (−4). Our results indicate that demand for subsistence foods cannot be covered in these highly populated areas, even with the surrounding paddy fields. For fuelwood, another important subsistence product for many, there is either a high surplus or a distinct lack thereof. Considering that both fuelwood and charcoal are by far the most common types of fuel used by households in Tanintharyi, such distinct positive or negative balances can be explained largely by the respective population densities. The high surplus in rural areas and unsatisfied demand in towns could increase trade in fuelwood and charcoal.

3.3. *Regional and local supply/demand mismatches*

3.3.1. *Frequency and intensity of mismatches at regional scale*

Combining all models, we identified on average four ES across Tanintharyi for which mismatches (supply < demand) were present (Fig. 6, left). No mismatches were detected in some parts within the protected areas. Only one ES was undersupplied in most other parts in and around protected areas as well as in regions dominated by villages and smallholder agriculture. However, overall, there are only few areas in Tanintharyi Region with such a negligible number of mismatches (≤1). Areas with a high number of mismatches (7–8) are just as rare. They are distinctly found in urban settings, e.g. in Dawei or Myeik, as well as along roads and in recently emerging development areas, as visible e.g. on the road to Thailand in the eastern part of the region. For the areas in between, characterized as mosaic landscapes with remaining natural forest patches interspersed with small-scale agriculture, we found a limited number of mismatches ranging between 1 and 3. Similarly, there was a rather low mismatch intensity in these mosaic landscapes (Fig. 6, right), indicating that while there may be an undersupply of some services, it is not severe. Considering the higher mapping uncertainties for mismatches compared to positively balanced ES (Fig. 5), there is a possibility that the displayed frequency and intensity of mismatches in Fig. 6 are slightly overestimated.

Although both frequency and intensity of mismatches exhibit similar patterns across the region, they are higher in urban and peri-urban areas and in areas with infrastructure. They are lower in protected areas and smallholder agricultural lands, but the mismatches are less pronounced in intensity than in frequency (i.e. in number). Combining all nine ES, we found up to 8 mismatches (mean = 3.9) in the study area, but with intensities of a maximum of 23 out of a potential 32 (if all mismatches had the highest possible inversed value of 4) and a mean of 9.5. So, while we identified several mismatches in large parts of Tanintharyi Region, the overall low intensity of those relativizes the impact on local stakeholders to a certain extent.

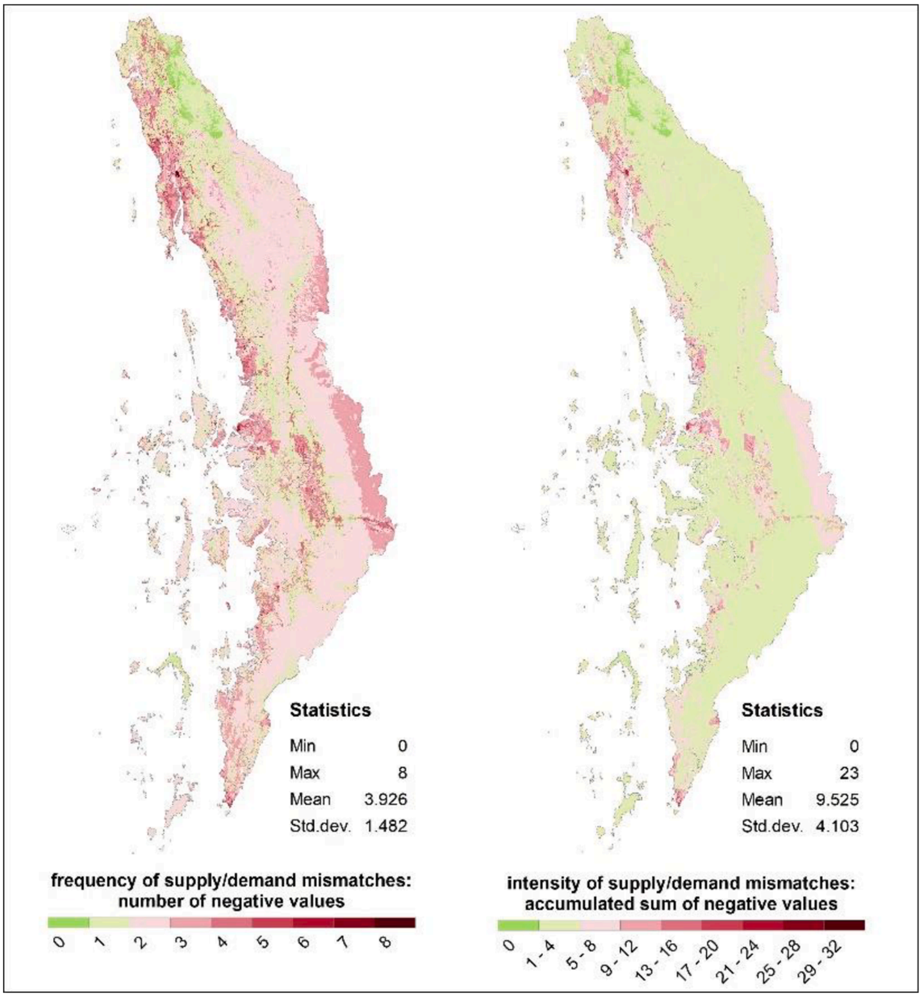


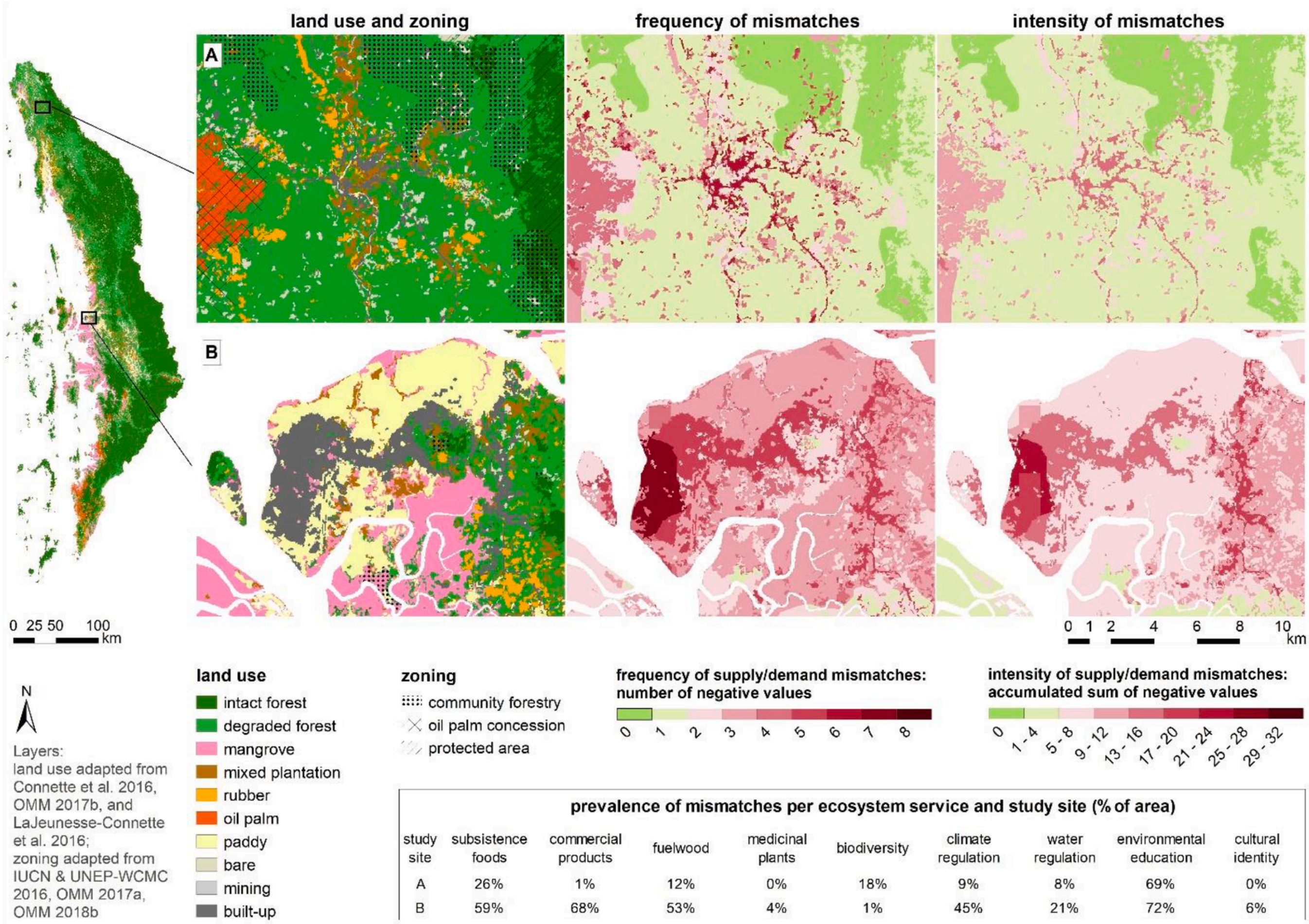
Fig. 6. Frequency and intensity of mismatches in Tanintharyi Region (*left*: frequency of supply/demand mismatches calculated as the number of negative ES balance values per raster cell; *right*: intensity of supply/demand mismatches calculated as the accumulated sum of negative ES balance values per raster cell).

3.3.2. Exploring mismatches in the context of two study sites

Although differences exist between the nine ES, there are some areas within Tanintharyi Region that are affected more by supply/demand mismatches. These include urban and other developed areas along roadsides with agricultural and/or mining concessions. In this section, we contextualize mismatches by zooming in on two study sites and inspecting ES mismatches in relation to land use and zoning. Fig. 7 shows the distribution of mismatches in these sites in terms of frequency and intensity.

Study site A in Yebyu township is characterized by several different zoning arrangements and related land uses. It includes not only part of the Tanintharyi Nature Reserve and adjacent community forests, but also an oil palm concession amid smallholder rubber and mixed plantations. Our results highlight first of all the importance of forest landscapes in providing multiple and balanced ES, also at local scale. We found that the number and intensity of mismatches is generally small in forest lands: in community forestry areas, there are no mismatches; in protected areas and other forested lands, there is one or more mismatches ranging in intensity from 1–4. Oil palm plantations, by contrast, are linked to several and intense ES mismatches. Since these plantations are under concession management, it is not evident whether local small-scale oil palm plantations would have fewer or less intense negative effects on ES. What can be seen, though, is that concession areas not planted with oil palm still limit the number of ES provided to local communities. For comparison, the scattered small-scale plantations in the area, mostly planted with rubber but also mixed with cashew and betelnut, are linked to 2–3 low-intensity mismatches. Thus, although they provide fewer regulating ES than the surrounding forests, these small-scale plantations are important for providing local communities with commercial products, fuelwood, and even some non-wood forest products such as foods or medicine. Overall, in study site A with its mosaic of land uses and zoning arrangements, the most frequent mismatches were found for environmental education (69% of the area – similar to regional level findings), followed by subsistence foods (26%) and biodiversity (18%).

Comparatively strong ES mismatches in urban areas are evident in study site B, which encompasses the town of Myeik and its surroundings, which include paddy fields, mangroves, and some lowland forests and tree crop plantations. In all built-up areas we identified severe mismatches, both in terms of frequency and intensity. In contrast to site A, even forested lands do not provide enough ES to compensate for this and satisfy local demand. Considering that the large demand for ES in more populated areas can hardly be covered with nearby supply areas, local communities therefore depend more on alternatives to ES. As an example, with limited land availability and thus few options to generate income from commercial crops, more urban people depend on non-agricultural jobs or businesses. Notable exceptions to the overall large mismatch areas are the two relatively small community forests, one covering intact lowland forest and the other covering mangroves. Most areas of both community forests present only one mismatch. According to Fig. 7, mangroves are related to fewer and particularly less intense mismatches compared to other land uses. Based on previous findings



study site	subsistence foods	commercial products	fuelwood	medicinal plants	biodiversity	climate regulation	water regulation	environmental education	cultural identity
A	26%	1%	12%	0%	18%	9%	8%	69%	0%
B	59%	68%	53%	4%	1%	45%	21%	72%	6%

Fig. 7. Ecosystem service supply/demand mismatches in terms of frequency (number of negative ES balance values per raster cell) and intensity (accumulated sum of negative ES balance values per raster cell) in two study sites of Tanintharyi Region (A: rural area in Yebyu township, B: Myeik town and surrounding area).

(see Fig. 2 in Section 3.1.1), mangroves are important providers of regulating services including biodiversity and climate mitigation as well as cultural identity and diverse subsistence and commercial products based on fisheries. Overall, a lower mismatch prevalence was found for biodiversity (1%) compared to study site A (18%). Apart from commercial crops, which are undersupplied on 68% of the land area, study site B also faces a lack of environmental education (72%), subsistence foods (59%), fuelwood (53%), and climate regulation (45%). The undersupply of climate regulation can be attributed to the large greenhouse gas emissions from towns and abundant paddy fields, as well as the naturally high demand for a good microclimate in a city with low air quality. This is particularly true for Myeik, which has several fish factories, and while there are climate-regulating mangrove areas south of Myeik, these provide only partial compensation.

4. Discussion

4.1. The role of forest frontier landscapes in providing local and global ecosystem services

Debates on tropical forest frontier landscapes have long revolved around land use trade-offs between agricultural production and environmental conservation (Mastrangelo and Laterra, 2015; Verburg et al., 2014) or between customary and elite rights that benefit some stakeholders while harming others (German et al., 2014; Schoneveld, 2014). Land sparing versus land sharing policies are a critical point of debate in many developing countries (Mertz and Mertens, 2017), but the picture is more nuanced. Stakeholder-driven and holistic ES assessments can contribute to the discussion by looking beyond biodiversity and agricultural productivity (Grau et al., 2013). Mosaic landscapes that are common in forest frontiers offer vast opportunities for sustainable development and the delivery of multiple ES (Muhamad et al., 2014; Pinillos et al., 2020; Tscharntke et al., 2005). Shifting cultivation, a traditional land use in Southeast Asian mosaic landscapes, also supports local livelihoods and ES outcomes where long fallow periods are upheld (Dressler et al., 2017). Our findings confirm the important role of these frontiers in providing various ES, especially for local stakeholders. Tanintharyi's mosaic landscape provides not only several agricultural subsistence and commercial products, but also many non-wood forest products and regulating services from remaining natural forests. Similar to our study area, Ahammad et al. (2019) found that rural and poor communities in Bangladesh use forest products mainly for subsistence rather than for income generation. Indeed, regulatory barriers limit commercial use of forests by communities in Southeast Asia (Gritten et al., 2015).

While forest and shifting cultivation lands are most closely linked to the culture of rural communities, local stakeholders perceive that all lands contribute in some way to their cultural identity, even new crops like rubber (Feurer et al., 2019). Environmental education, also a cultural ES, is less directly linked to land uses. In the applied models, traditional land uses are associated with informal knowledge exchanges, while newer land uses or management forms such as community forestry are linked to formal agricultural or silvicultural training. Traditional and indigenous knowledge contributes to the conservation and sustainable management of remaining natural forest and shifting cultivation areas (Siahaya et al., 2016), whereas formal education can enable the sustainable intensification of existing agricultural lands (Tscharntke et al., 2005), including agroforestry. Overall, it is evident that local ES benefits go beyond biodiversity, climate regulation, and agricultural production, and that they are key for all aspects of human well-being in forest frontier landscapes.

From a global perspective, larger forest complexes are critical for non-material services. Our maps show a high supply of biodiversity and climate regulation, both of which are in severe decline across the globe (IPBES, 2019). While regulating ES are also highly valued by local stakeholders, the benefits perceived by them differ from those required at the global level. Considering climate services, for example, rural communities perceive fewer direct benefits from carbon sequestration but appreciate a regulated microclimate and better air quality (Feurer et al., 2019). They perceive climate services as regulating temperature and humidity at micro or regional scale (Haines-Young and Potschin, 2018). In coastal areas, we found a higher local demand for climate regulation, which confirms the findings of Bennett et al. (2014) that coastal communities are more sensitive to the impacts of climate change. For rural households, biodiversity is represented through a variety of non-wood forest products, pollination services that support their agricultural livelihoods, and a safety net that gives them a sense of security. Related to this, Feurer et al. (2019) found in Northern Tanintharyi that medicinal plants are valued for potential future benefits or in times of need, rather than for current use, and should therefore be conserved.

However, biodiversity conservation should go beyond implementing large protected areas, as these often contain customary lands and could negatively affect the livelihoods of people living there (Schleicher et al., 2019). Conservation must be coupled with adequate land management in surrounding areas, including buffer zones to ensure the long-term availability of multiple ES and connecting elements to safeguard biodiversity at landscape scale (Kremen and Merenlender, 2018). Acknowledging both that local communities are important actors in frontier landscapes and that they highly value the various ES provided (Muhamad et al., 2014), sustainable development planning and policy must be participatory, include relevant customary land rights and practices (Dressler et al., 2017), and enable tenure security (Robinson et al., 2014).

4.2. Options for reducing mismatches in affected areas

Improving ES flows is critical in areas affected by high supply/demand mismatches, where the inability of local stakeholders to access service-providing areas reduces welfare (Kmoch et al., 2021) and, in the long term, their adaptive capacities (Ensor et al., 2015), eventually inducing conflicts. Sustainable planning for landscapes must consider different stakeholder perspectives. Protected areas may hinder forest loss and conserve biodiversity, but their effectiveness strongly depends on their design, governance, restrictions (Schleicher et al., 2019), and other factors such as road networks, accessibility, and human pressure (Leberger et al., 2020). In highly populated areas, rights-based approaches to forest conservation can improve environmental and livelihood outcomes simultaneously (Porter-Bolland et al., 2012). Conservation should thus not be totally separated from sustainable use. The example of community forestry in our study confirms that rights-based approaches can achieve multiple goals. Community forestry areas were linked to fewer supply/demand mismatches than other land uses, including protected areas. Several other studies have also shown the contribution of community forestry to rural livelihoods, poverty alleviation, erosion control, climate change mitigation and adaptation, and biodiversity (Birch et al., 2014; Feurer et al., 2018; Pandit and Bevilacqua, 2011).

In addition to forest-based land uses, Kremen and Merenlender (2018) suggest enhancing biodiversity in working agricultural lands, while Reith et al. (2020) found that including large shares of agroforestry in landscapes enhances the variety of ES provided. Pinillos et al. (2020) suggest that the simultaneous delivery of multiple ES requires a combination of both land sharing and land sparing strategies. Modelling different policy scenarios in a frontier landscape in Indonesia, Law et al. (2017) found that mixed strategies were most effective in supporting several provisioning and regulating ES, provided that approximately one-third of the landscape was conserved for biodiversity. While our research did not provide insights on potential scenarios, it did indicate that areas with a mosaic of land uses including smallholder plantations and natural forests cause fewer mismatches. Further, our results provide evidence that land sparing, a concept founded on ecological principles, can have strongly adverse social outcomes. Oil palm concessions presented low ES supply (and, consequently, more mismatches) and limited flows for local stakeholders. In high-supply areas, Boesing et al. (2020) suggest strengthening flows as a main goal in land sparing policies. In mixed landscapes, efforts need to focus more on increasing supply or lowering demand (ibid.). To achieve the highest local ES outcomes, we propose a holistic approach to landscape planning that consists of some protected areas with well-defined, community-managed buffer zones and a mosaic of optimized smallholder agricultural systems.

Consistent with other studies (Baró et al., 2016; Burkhard et al., 2012), we found a higher number and intensity of mismatches in urban and peri-urban areas. Even though low urbanization rates have been observed in Tanintharyi in the past, this could change once the Special Economic Zone in Dawei has been completed (Walsh, 2015), further enhancing demand for ES. But towns generally provide more options on ES substitutes such as electric or gas stoves to replace fuelwood, or jobs to reduce dependency on agricultural incomes, and so high mismatches in urban areas may not have as much of an impact on local stakeholders as estimated here. Globally, most efforts to enhance provision of ES in cities are related to green infrastructure including tree planting (Geneletti et al., 2020). Additionally, small gardens and trees within housing compounds can play a considerable role in securing some ES at local scale. In all three towns of Tanintharyi, we observed numerous home gardens, which provide the owners with subsistence foods, fruit for religious ceremonies, as well as shade. However, due to their small scale, these ES are not visible in our results and may have led to slightly overestimated mismatches in towns. Adjacent areas also need to be considered when evaluating mismatches (Baró et al., 2016). Our findings indicate, however, that it is nearly impossible for a large population in urban areas to cover their multiple ES demands with surrounding lands. As all towns in our study site are coastal, the value of mangroves is evident. Mangrove forests have few mismatches and a portfolio of diverse ES, even storm protection (Richards and Friess, 2016), a crucial service that was however not considered in our assessment. Mangroves are therefore integral for coastal urban planning. In sum, while urban and peri-urban areas may not be able to reach balanced ES outcomes, mismatches can be reduced to a certain extent, either by increasing supply (tree planting, home gardens, high-provisioning land uses surrounding urban spaces) or by reducing demand through improved access to man-made alternatives and more sustainable technologies.

4.3. Limitations, lessons learnt, and moving forward

Using comprehensive BN for nine ES, this study modelled and mapped their supply, demand, flow, and mismatches at a scale unprecedented for tropical regions. Data scarcity was addressed by combining secondary data with qualitative data collected with different stakeholders across Tanintharyi Region. Our research aimed to adhere to the recommendations for ES mapping provided by Willemen et al. (2015), including robustness, stakeholder relevance, and transparency. We found that the latter implies a modest trade-off with the former two, as the inclusion of a wide range of variables and stakeholders inherently obscures ES models and reduces clarity for map users. For smaller-scale studies and projects aiming to implement findings from ES assessments, a more holistic co-production of knowledge is recommended (Gritten et al., 2015; Pandeya et al., 2016).

Regional-level mapping still comes with some limitations on stakeholder involvement. Although our results give a good overview of ES outcomes for the majority of Tanintharyi's highly diverse population (smallholder farmers, forest-dependent communities, and coastal residents), some groups may be underrepresented. Regional assessments, particularly those in ecologically and culturally diverse tropical frontier landscapes, inherently face this challenge of representativeness, but we argue that they are nonetheless important baselines for landscape planning and policy, provided that limitations are clearly communicated. Although data sets were available for several variables in Tanintharyi Region, our study faced limitations related to data quality and timeliness. Further, underlying assumptions of the models are primarily based on qualitative data, which adds value but often implies more multifaceted outputs. In the absence of quantitative data, it can be assumed that such uncertainties widened the probability distributions of the results on ES supply, demand, and particularly flow. Mapping the evenness index is useful as it discloses variations in the results and reflects, to a certain extent, these uncertainties. The overall high evenness indices for ES flows identified in this study confirm the difficulties of integrating flow and address equity in ES assessments (Ramirez-Gomez et al., 2020) and call for more empirical evidence on the implications of zoning and tenure rights. Given the sensitivity of the results in respect to model design and input data, the outputs should be regarded as approximations of the actual situation and not as final values.

An advantage of BNs is that they can be easily updated once new data becomes available, and that temporal dynamics could be included, e.g. with the gBay tool (Stritih et al., 2020). The inclusion of temporal dynamics to assess ES extirpation over time (Boesing et al., 2020) would be a relevant next step but is hampered in regions suffering from data scarcity. Monitoring information on land use distributions is particularly important in forest frontier landscapes where land use changes occur rapidly. Further, limited land tenure data reduces the reliability of mapped ES flows. It is therefore crucial to update tenure data and monitor progress made in customary land rights. Future use of these ES models could include policy scenario analysis, similar to recent work in Indonesia (Law et al., 2017). We believe that mapping supply/demand mismatches is a useful tool for identifying sustainable development pathways that closely involve local stakeholders. Finally, integrating considerations of flow into these mismatch analyses is key to enhancing the well-being of local communities.

5. Conclusions

Combining comprehensive BN models with GIS, this study mapped the supply, demand, and flow of nine ES for local stakeholders in a forest frontier landscape in Tanintharyi Region, Myanmar, using values between 1 (very low) and 5 (very high). Across the region, we found a high supply of biodiversity (mean = 4.7), climate regulation (4.7), cultural identity (4.6), fuelwood (4.5), medicinal plants (4.5), and water regulation (4.3) – with particularly high supply in forest areas. Flat lands and shifting cultivation areas provide high amounts of subsistence foods, but few areas provide commercial products (1.3) and environmental education (1.4) for local communities. Local demand is particularly high for biodiversity (4.8), environmental education (4.1), and subsistence foods (3.9), and for all ES, it increases with population density. Urban and other rapidly developing areas face the strongest supply deficits. Mapping such supply/demand mismatches for all nine ES showed that most occur in urban areas or degraded forest lands with up to eight and three mismatches, respectively. In contrast, mosaic landscapes consisting of remaining patterns of natural forests and smallholder agricultural plantations presented very few mismatches ($\leq$1). However, the degree to which the respective ES are undersupplied is generally low, especially in rural areas. Zooming in on two study sites – in Yebyu township and in and around the town of Myeik – we found that mismatches are not only related to land use but also to zoning and land tenure arrangements such as concession lands, protected areas, or community forests. Our results show that local stakeholder access to ES is restricted in oil palm concessions and protected forests. This is also reflected in high mismatches. On the other hand, community forests perform much better both in terms of limited mismatches and secure ES flow.

In addition to globally important ES such as biodiversity or climate regulation, our comprehensive study highlights that local communities value subsistence products as well as educational services provided by nature and related institutions. We contributed to ongoing ES research by spatially applying complex BN for a data-scarce region. With a local stakeholder perspective, our findings confirm the importance of mapping mismatches, as these particularly affect ES outcomes for rural communities. Regional assessments that consider mismatches can inform potential policies or management interventions in a more targeted way. With zoning and land tenure having an impact on both supply/demand mismatches and flow, we recommend that future ES research in tropical forest frontiers should always integrate the question of access and use rights. In future scenarios for Tanintharyi Region, local rights to not only access but also manage land and natural resources are key to assessing and ensuring effective ES outcomes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work of this paper.

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